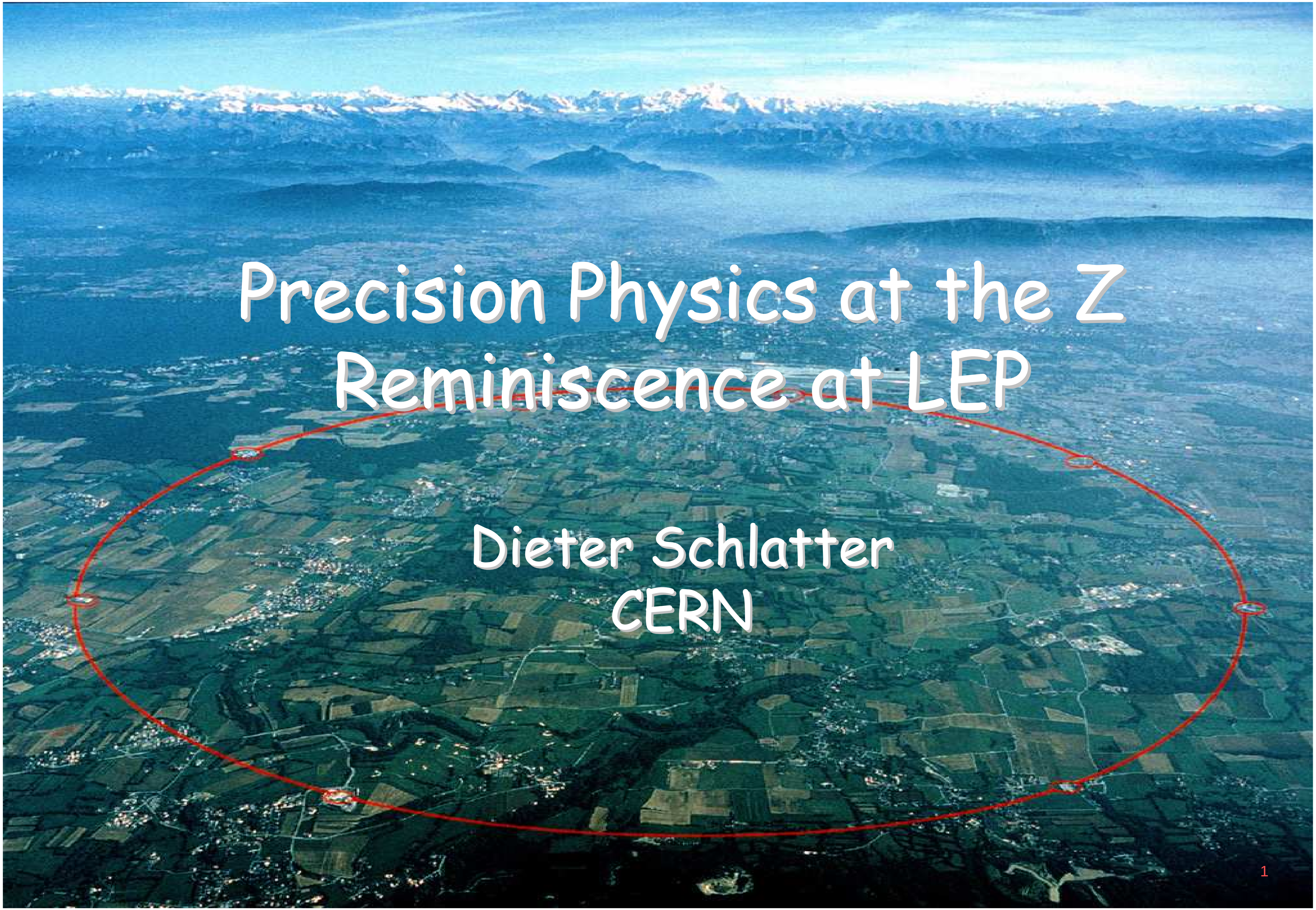
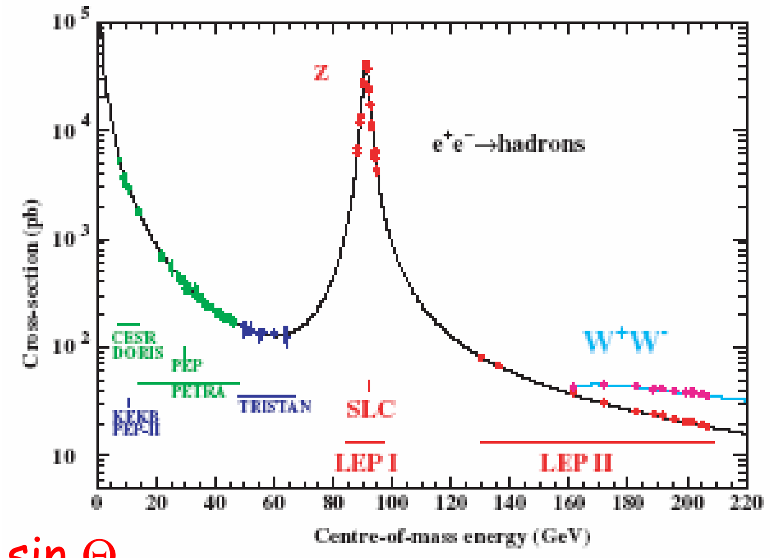


Precision Physics at the Z Reminiscence at LEP

Dieter Schlatter
CERN

Precision Physics at the Z, LEP: 1989-1995



LEP and the 4 Experiments:

200 pb^{-1} integrated luminosity
15.5 million Z decays to quarks
1.7 million decays to charged leptons

Measurements:

Z-Line shape, σ^0, Γ_Z, M_Z $\rightarrow N_\nu$
Z decays
Angular distributions, lepton asymmetries $\rightarrow \sin\Theta_{eff}$
τ decays $\rightarrow \alpha_s(m_\tau)$
etc, etc, …

Generators/SM Pgms:

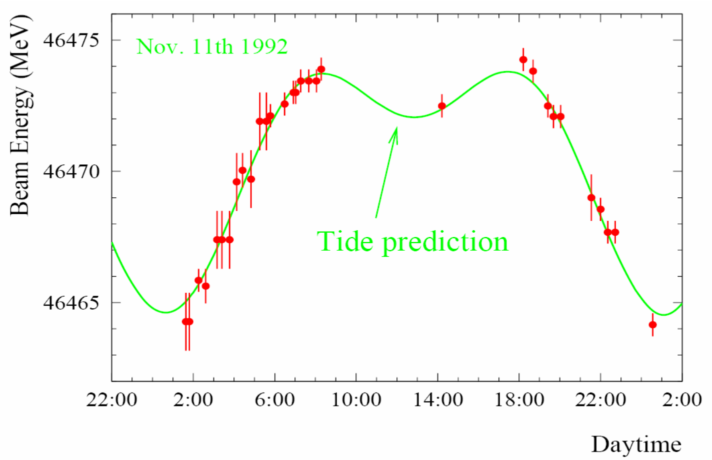
KORALZ, BHLUMI, KKMC, BHWIDE, TAUOLA (S. Jadach et al.)
PHOTOS (E.Barbiero, B.vanEijk, Z.Was)
BABAMC (F.A. Berends et al.), ALIBABA (W. Beenakker et al.)
JETSET (T. Sjostrand), HERWIG (G. Marchesini, et al.), ARIADNE (L. Lonnblad)
ZFITTER (D.Y. Bardin, et al.), TOPAZ (K. Miyabayashi, et al.)
etc, etc, …

The Instruments/Actors

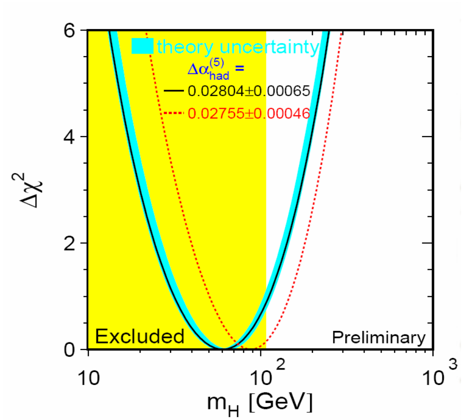
- LEP Collider: clean and stable machine, high luminosity
- 4 Experiments: well functioning detectors, only upgrades for b-physics (Si vertex detectors) and precision luminosity measurement (SiW calorimeters)
- Theorists providing high precision calculations

Working groups with members from all three (new style)

LEP Energy WG (LEP E calibration)



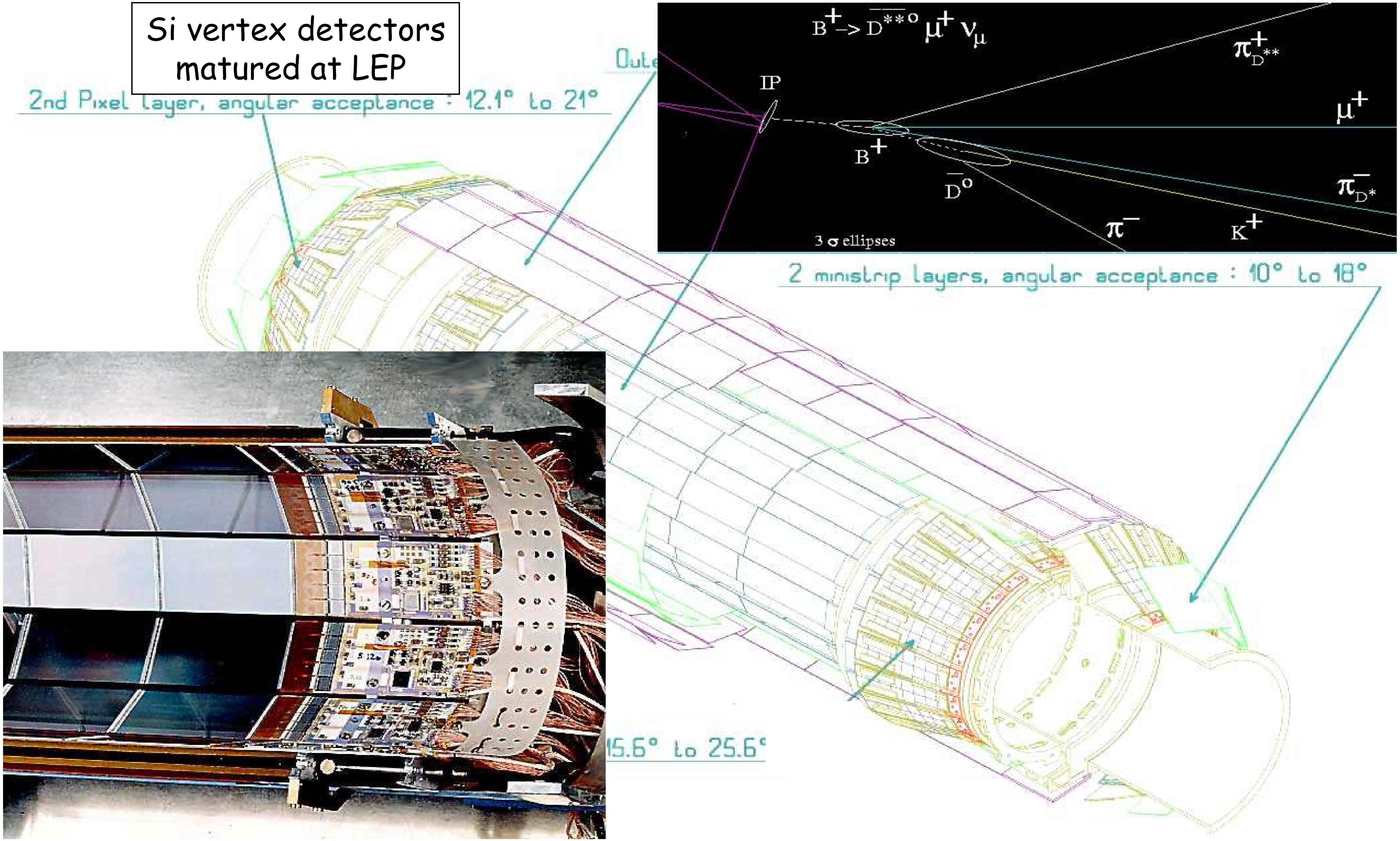
LEP Electroweak-WG
(Combination and SM fits)



Physics Report, 2005, *"Precison EW Measurements on the Z Resonance"*

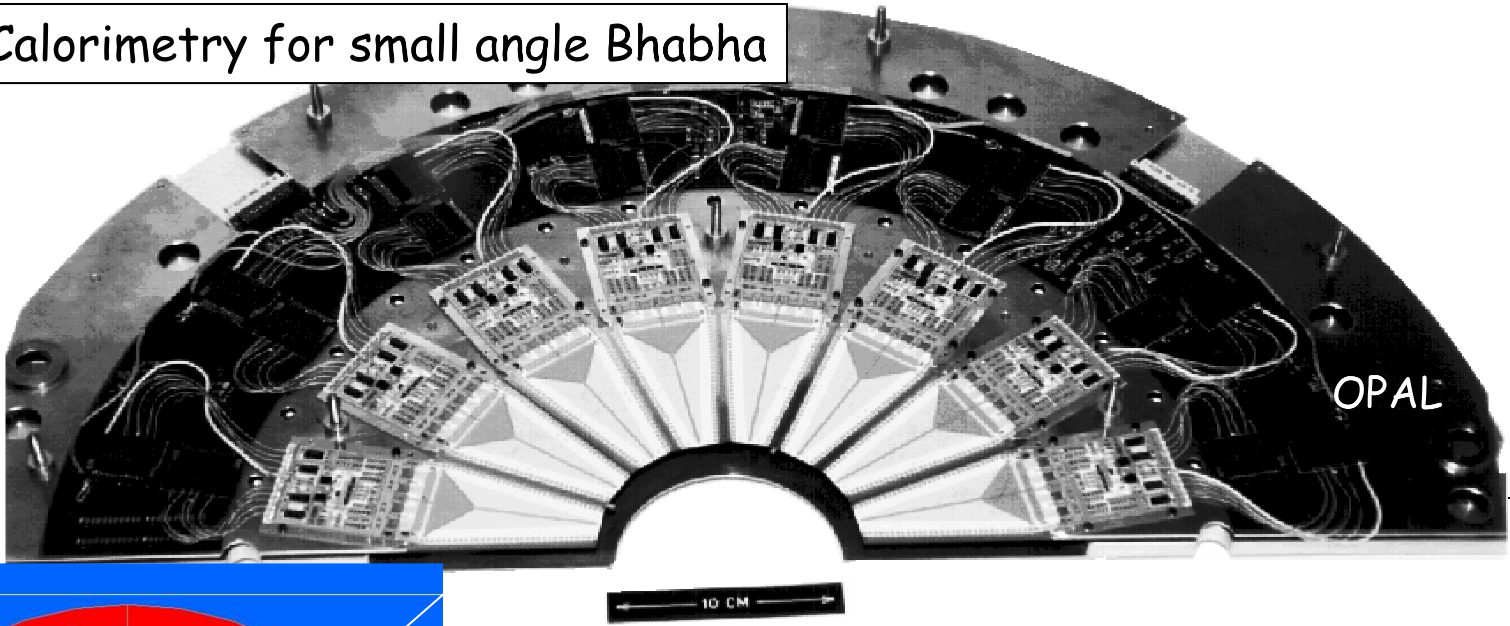
New detector concepts

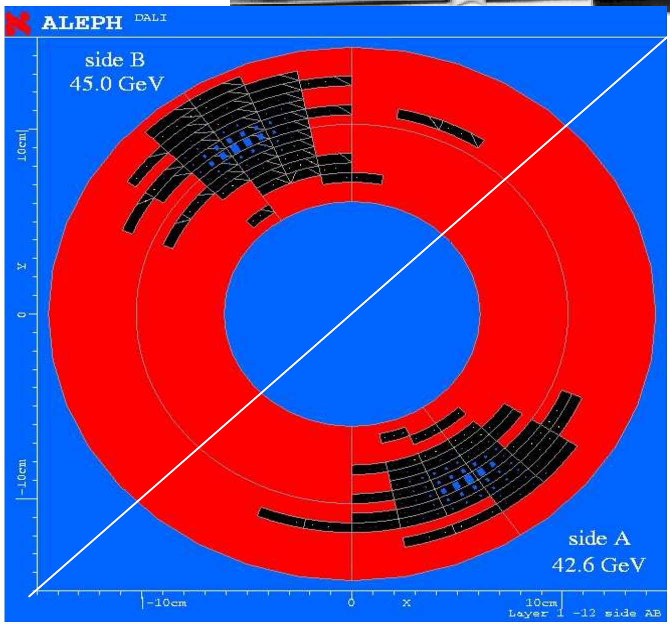
Si vertex detectors matured at LEP

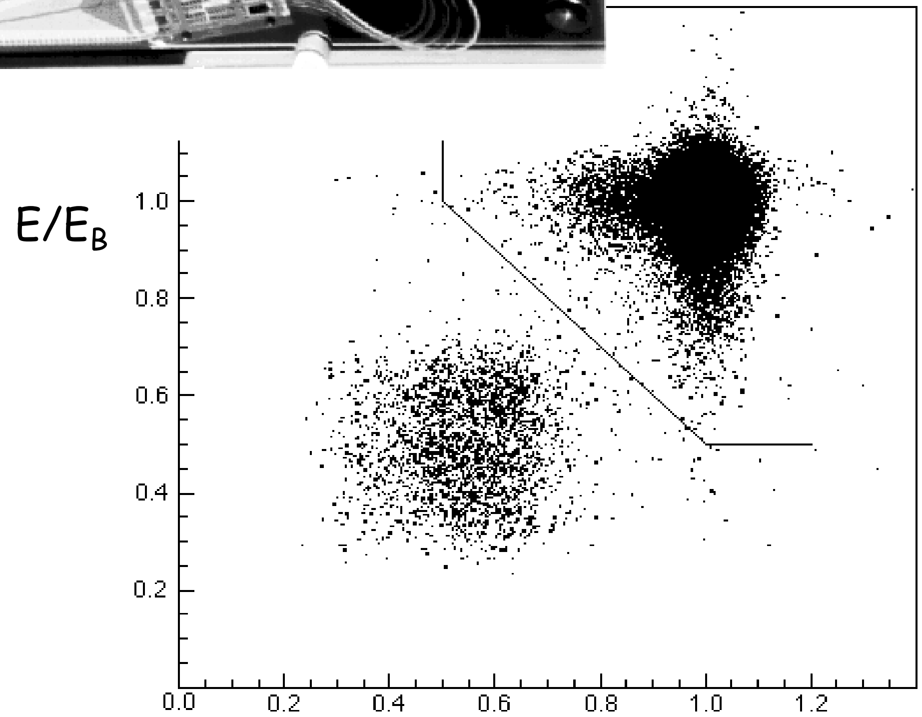


New detector concepts II

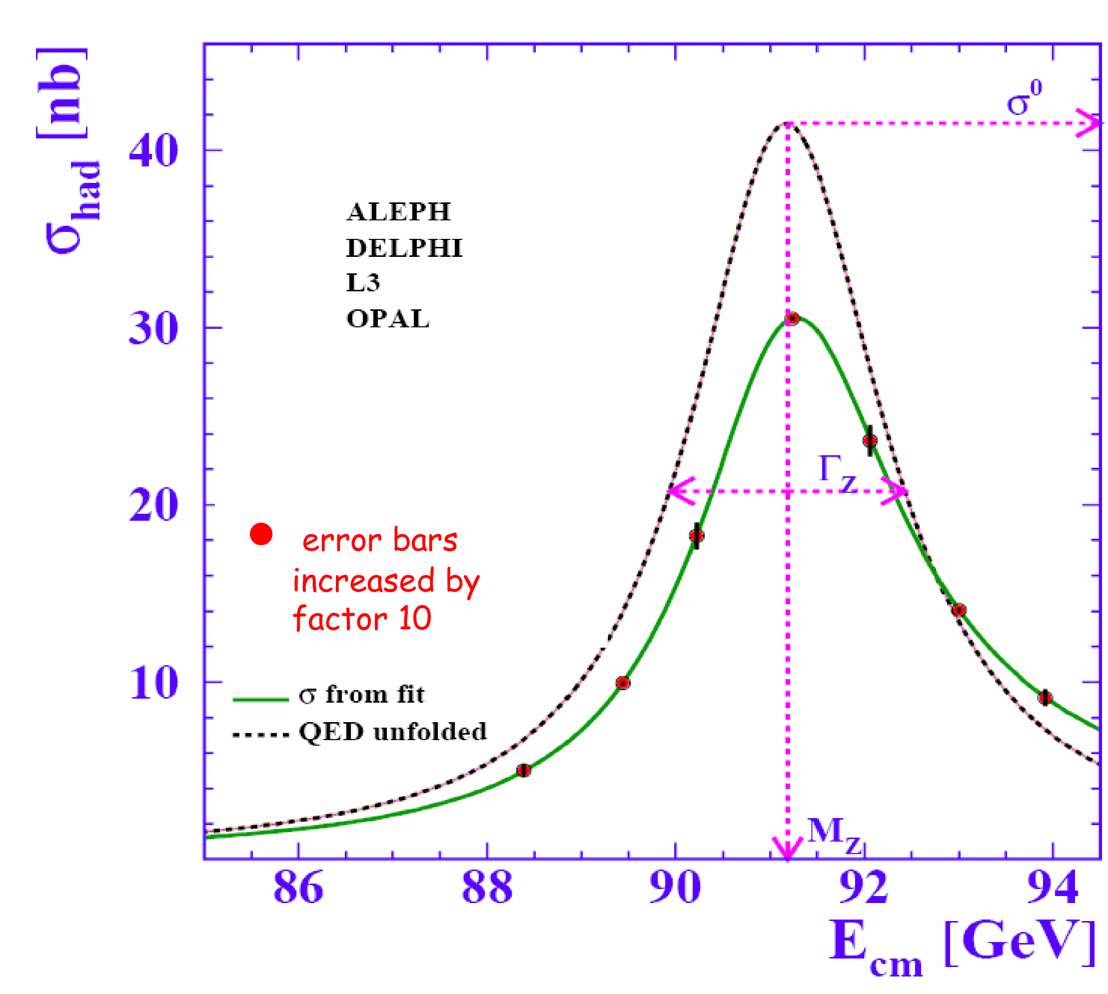
SiW Calorimetry for small angle Bhabha







Z Lineshape



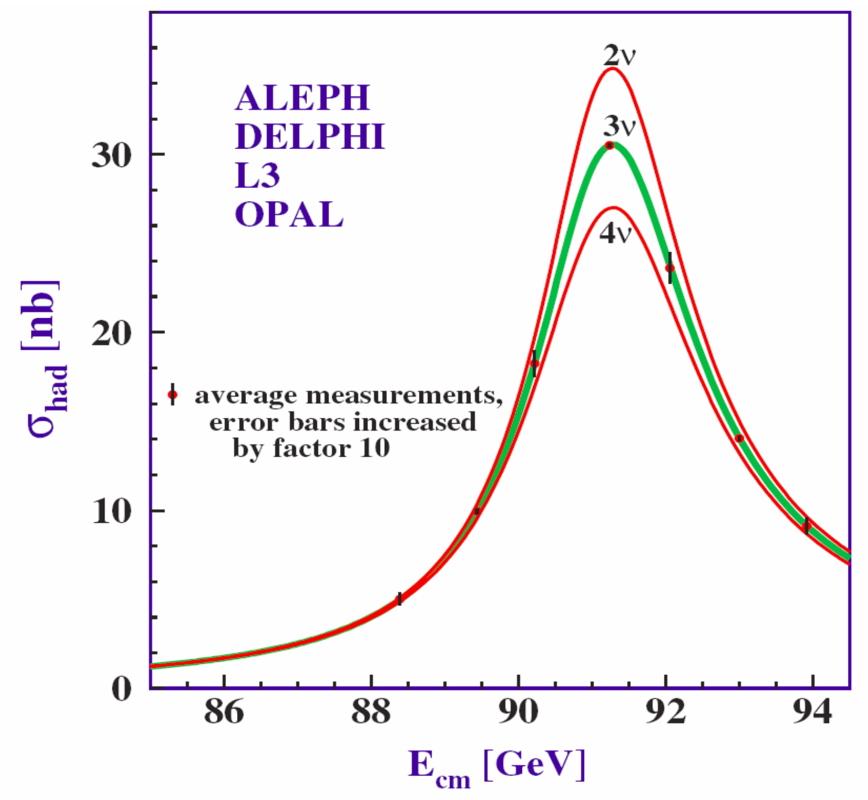
peak X-section
→ N_ν to 2.7‰

$\delta\sigma^0$ is dominated by the uncertainty in absolute L (~1‰)
→ Luminosity measurement

The final hadronic cross section, measured and QED deconvoluted.

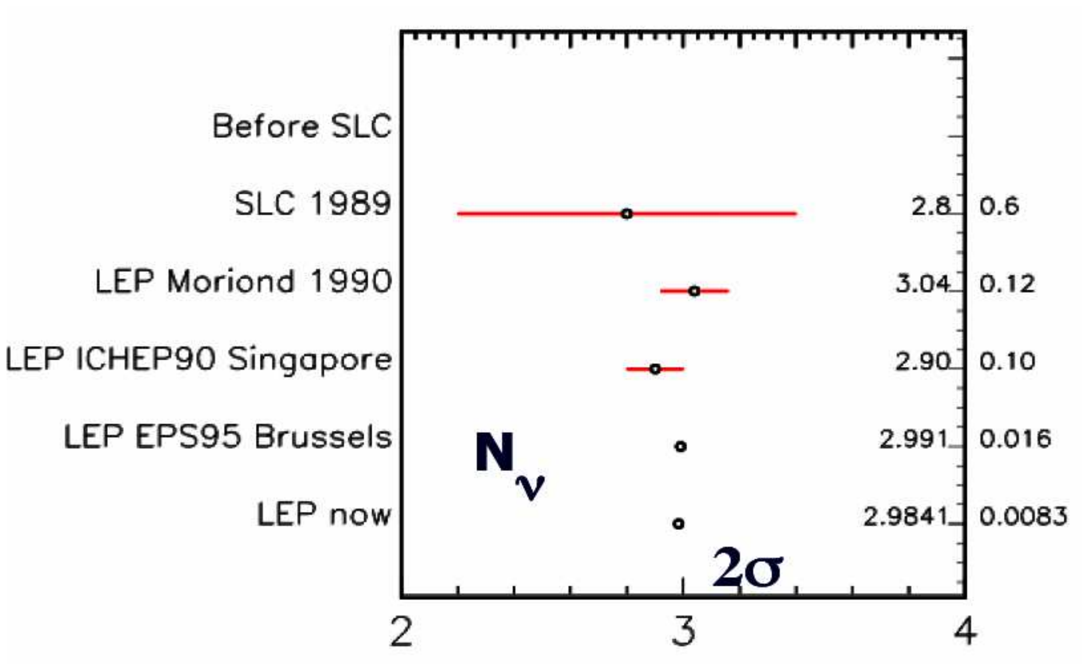
M_Z to 20 ppm → LEP energy calibration

Number of light neutrinos, N_ν



first publications in 1989

from Γ_{inv}/Γ_{ll}



2006 EWWG

$N\nu$ = 2.984 ± 0.0082
(from L: δ = 0.0046)

Luminosity determination: Precision race!

In 1989, luminosity uncertainty was still important

- Detectors upgraded with SiW precision calorimeters
- Theory: from $O(\alpha)$ to $O(\alpha^2)$ LL YFS exponentiated matrix element.
  2005: "All four collaborations use BHLUMI4.04, the best available Monte Carlo generator for small-angle Bhabha scattering.."

Uncertainty (%) in small angle Bhabha cross section

	'89	'91	'92	'96	'99
Expt	1.5	0.6	0.1 SiW calo.	0.09	0.06
Theory	1.0 BABAMC O(a)	0.3 BABAMC LUMLOG	0.3	0.1 BHLUMI	0.06 BHLUMI

F. A. Berends, et al.
NP.B304(1988)712

S. Jadach et al.
CPC102(1997)229

S. Jadach, M.Melles, BFL.Ward, SA.Yost,
PLB 450(1999)262

Polarisation at LEP

Polarization is a slow and delicate process which requires a lot of care and special machine conditions !

Ideal machine :

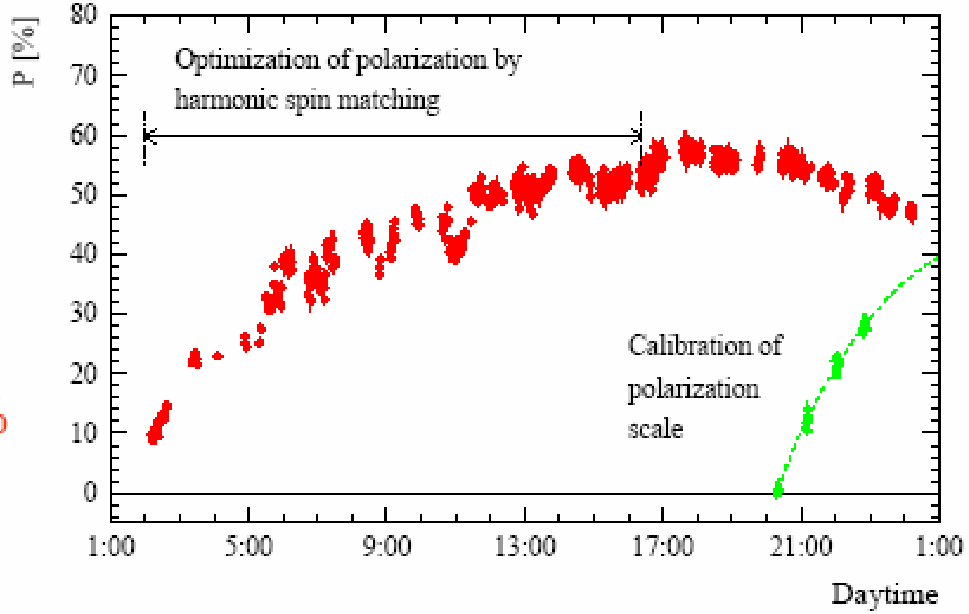
$P_T^{max} = 92.4\%$

At LEP :

record $P_T = 57\%$

routine $P_T = 5 - 10\%$

Up to 60.6 GeV



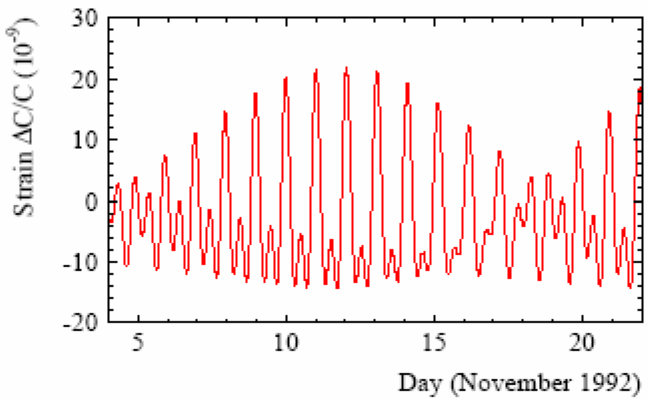
10.10.2000

At LEP resonant depolarization is sensitive to circumference changes of $\Delta C/C \sim 10^{-9}$!

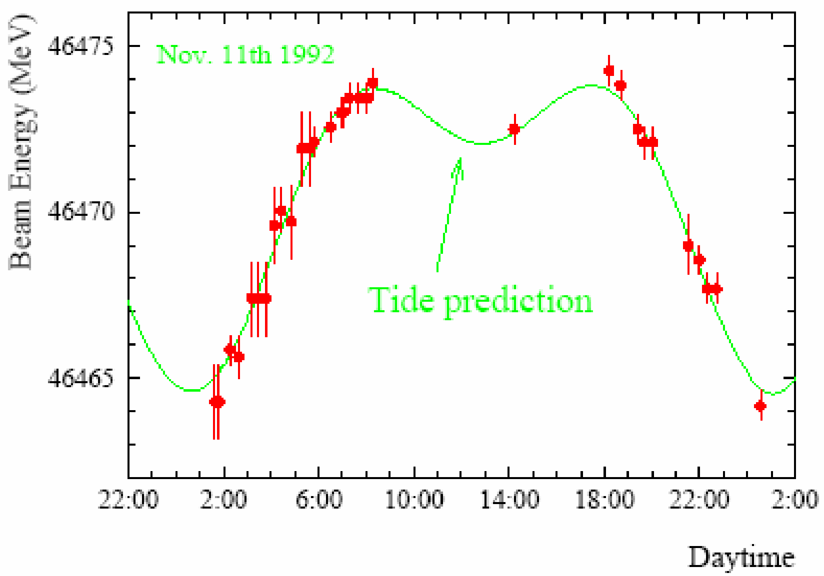
1991 : the first calibrations revealed unexplained fluctuations of the beam energy. A SLAC ground motion expert suggested… tides !

Earth tides :

- The Moon contributes 2/3, the Sun 1/3.
- NO 12 hour symmetry (direction of Earth rotation axis).
- Not resonance-driven (unlike Sea tides !).
- Accurate predictions.



Fall of 1992 : The historic tide experiment !



The total strain is 4×10^{-8} (ΔC = 1 mm)

La Lune trouble le CERN

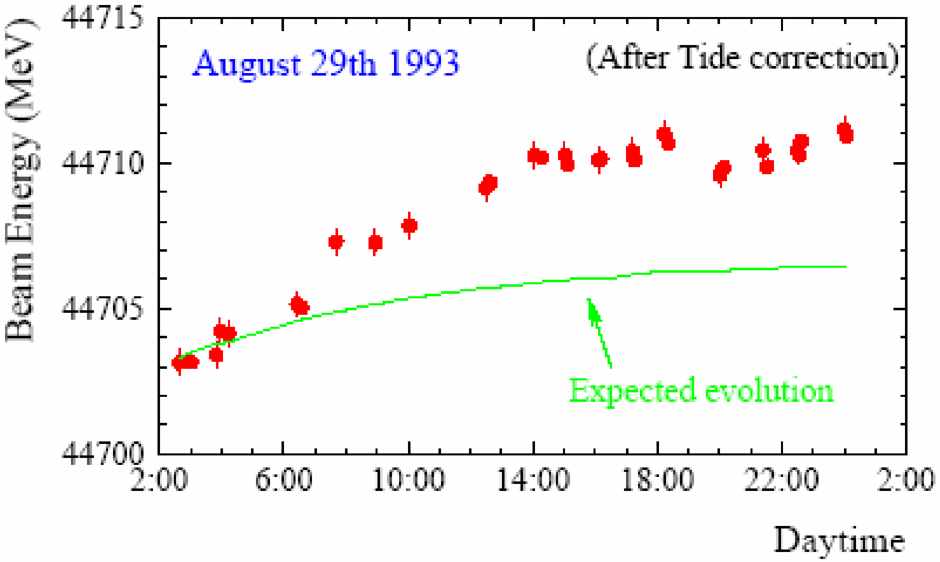
L'énergie des particules circulant dans l'anneau du LEP se modifie en fonction des phase lunaires.

The Crack in the Model

Spring of 1994 : the beam energy model seemed to explain all observed sources of energy fluctuations...

EXCEPT :

An unexplained energy increase of 5 MeV was observed in ONE experiment.



It will remain unexplained for two years…

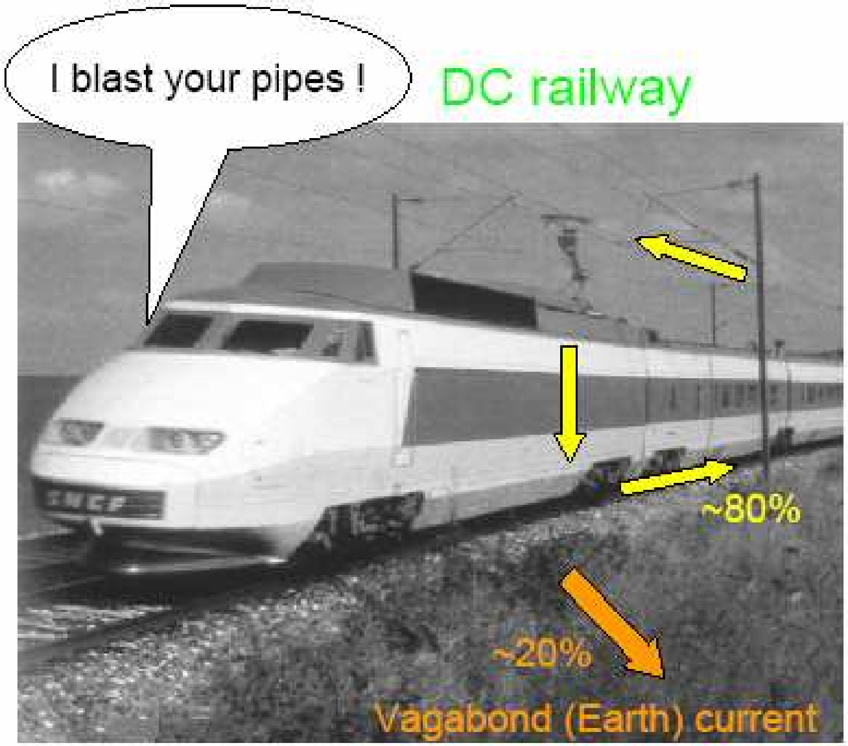
Pipebusters

The explanation was given by the Swiss electricity company EOS...

Vagabond currents from trains and subways

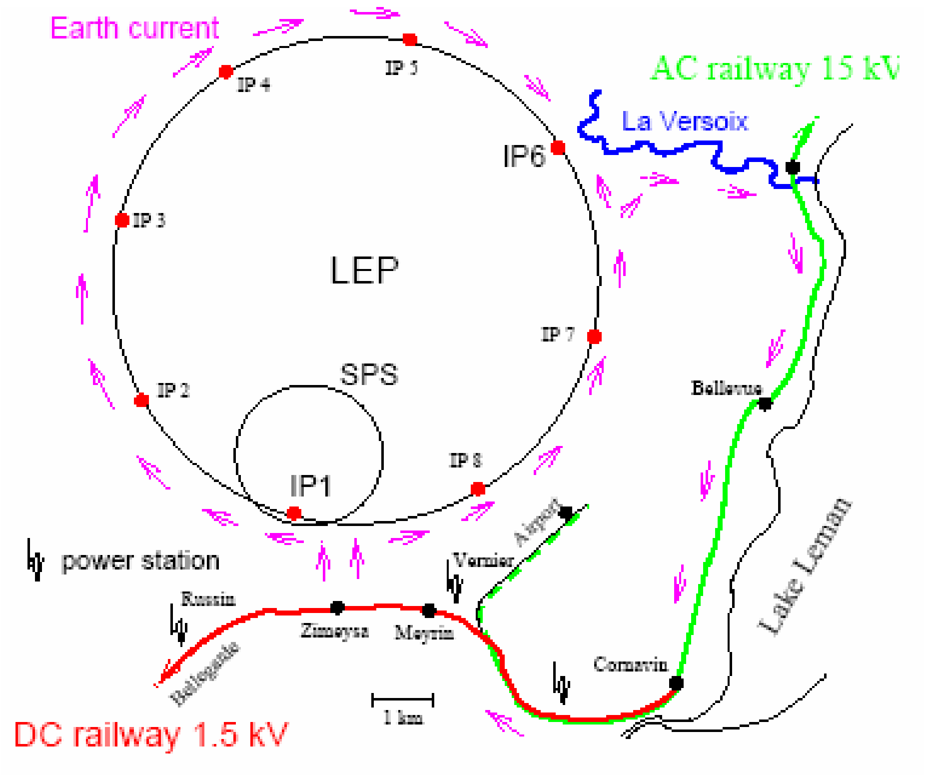
↓

Source of electrical noise and corrosion
(first discussed in …1898 !)



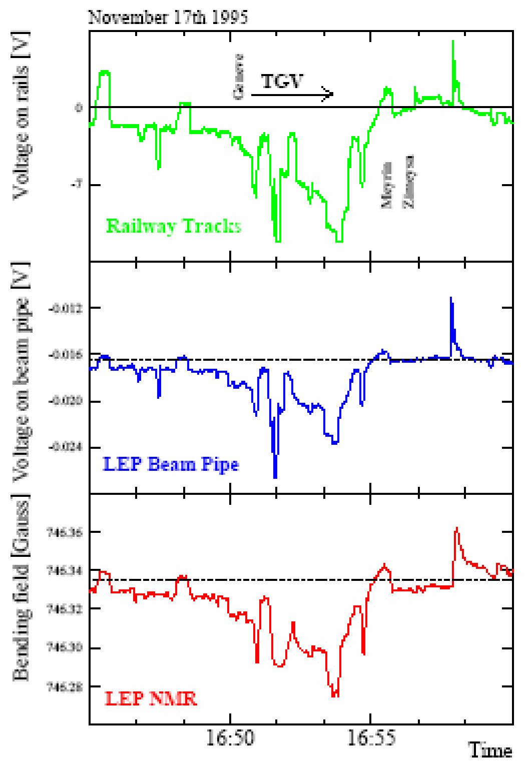
LEP Energy Saga (from J. Wenniger at LEP Fest 2000)

A DC current of 1 A is flowing on the LEP vacuum chamber.



November 1995: Measurements of
- The current on the railway tracks
- The current on the vacuum chamber
- The dipole field in a magnet

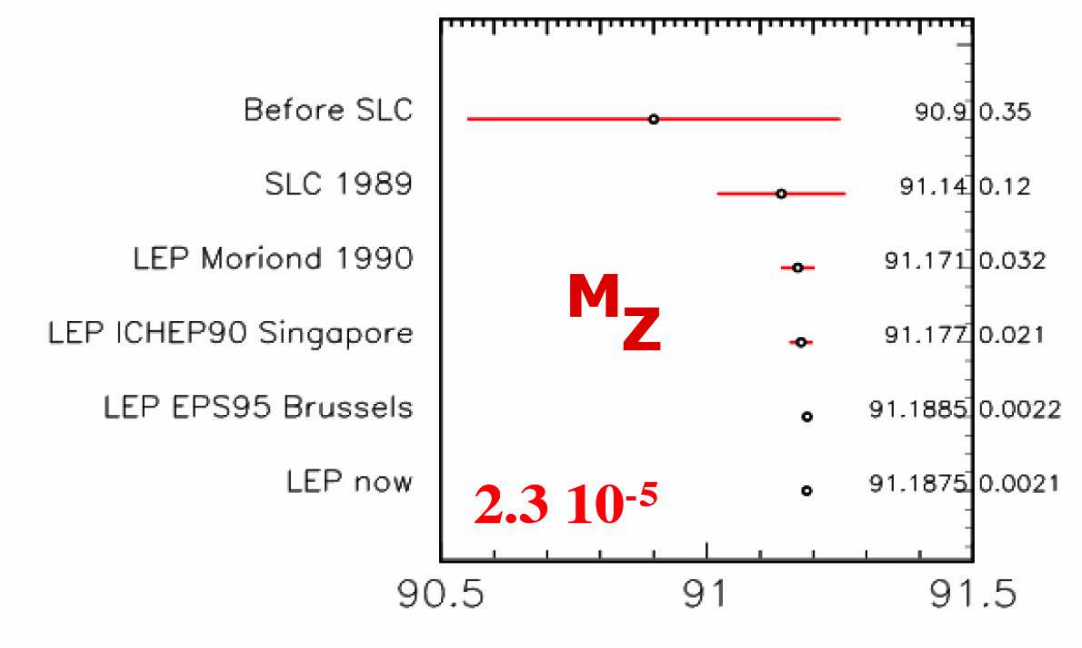
correlate perfectly!

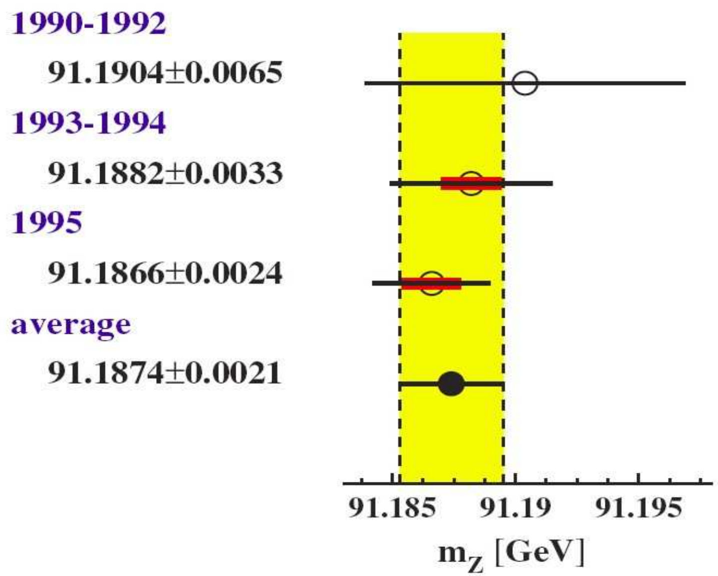


Z Mass

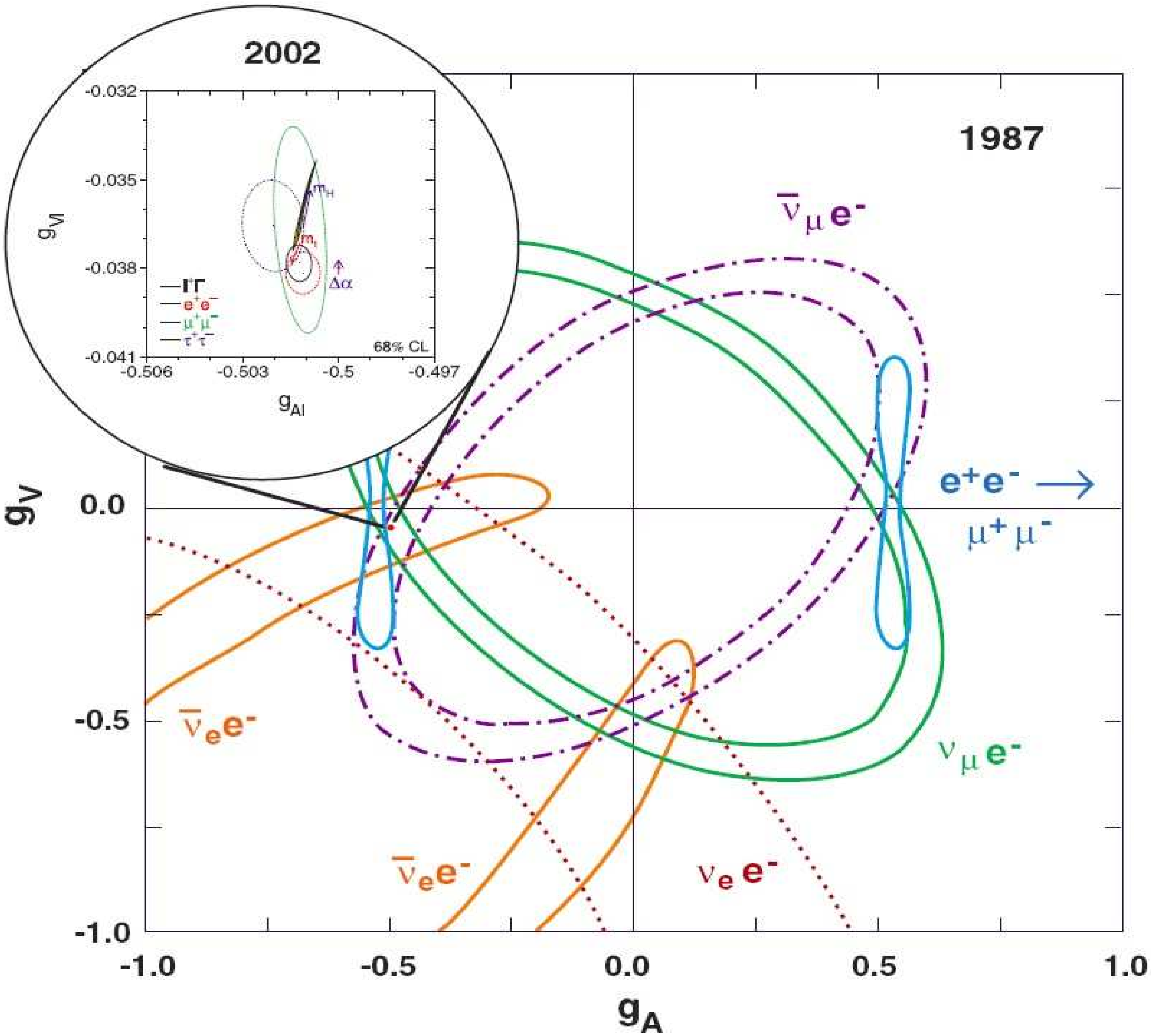
LEP Energy Working Group between physicists from LEP machine and experiments led to remarkable precision in M_Z (1.5 MeV).

M_Z =91.1875 ± 0.0021 GeV
measured to 23 ppm!
M_Z and G_F are the two fixed points of SM!



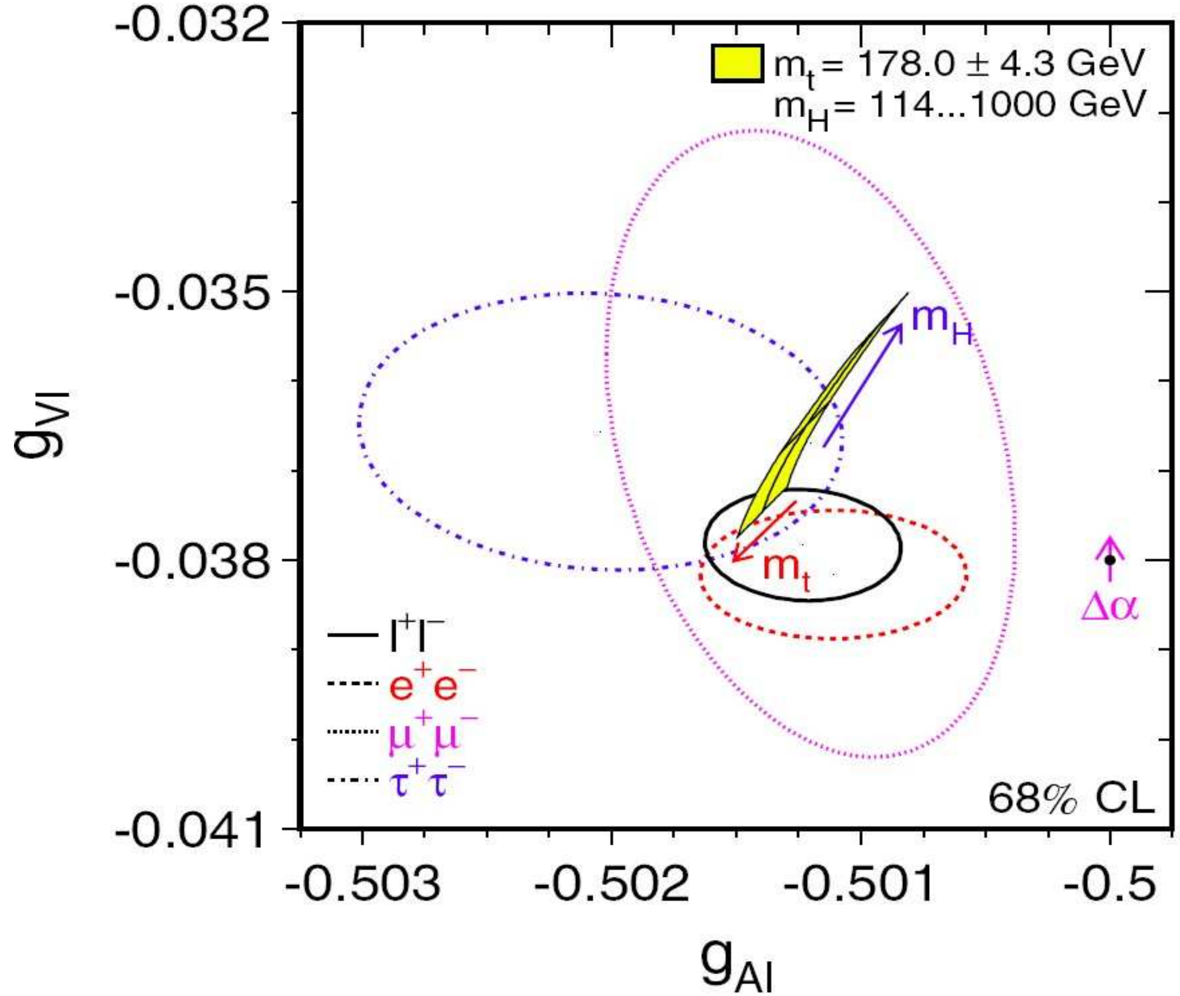


Z couplings to e, μ, τ



Z couplings to e, μ, τ

Contributions: from LEP A_{FB}, Γ_{ll} and from SLD A^0_{LR}



Neutral current lepton universality observed at the few ‰ level.

Z couplings to e, μ, τ

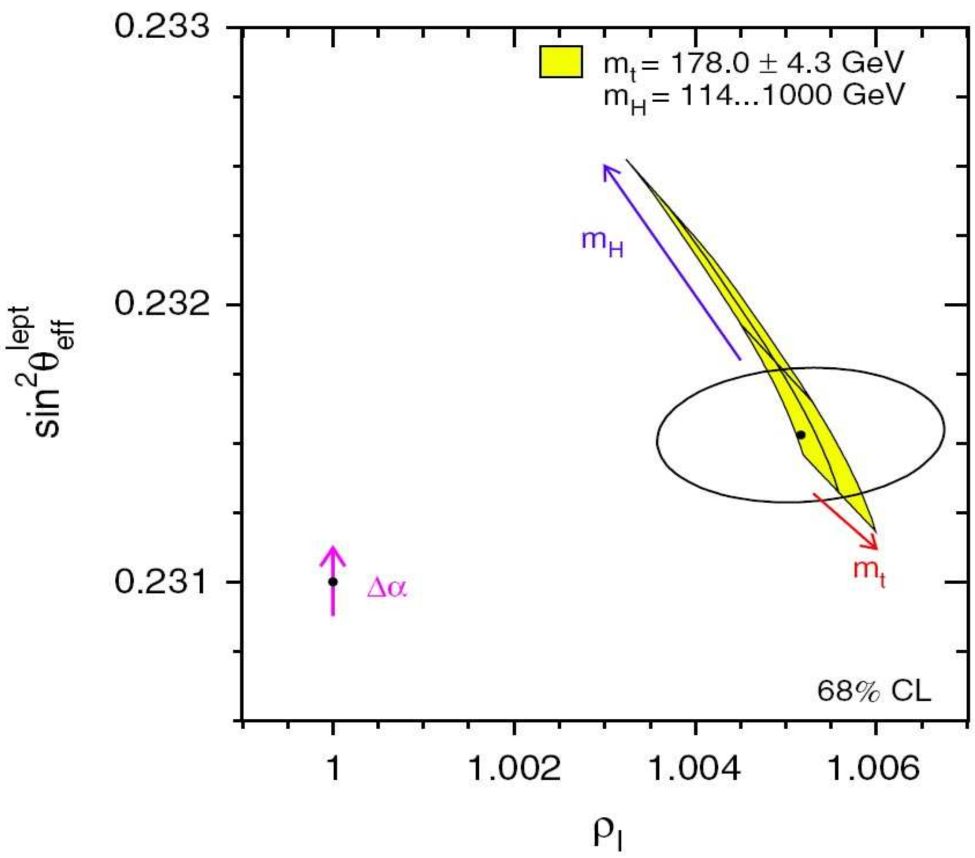
ρ_l Parameter

$\rho_{Vl} = \frac{1}{2}\sqrt{\rho_l}\,(4 \sin^2\theta_{eff}^{lept} - 1)$

From leptonic width, Γ_{ll}

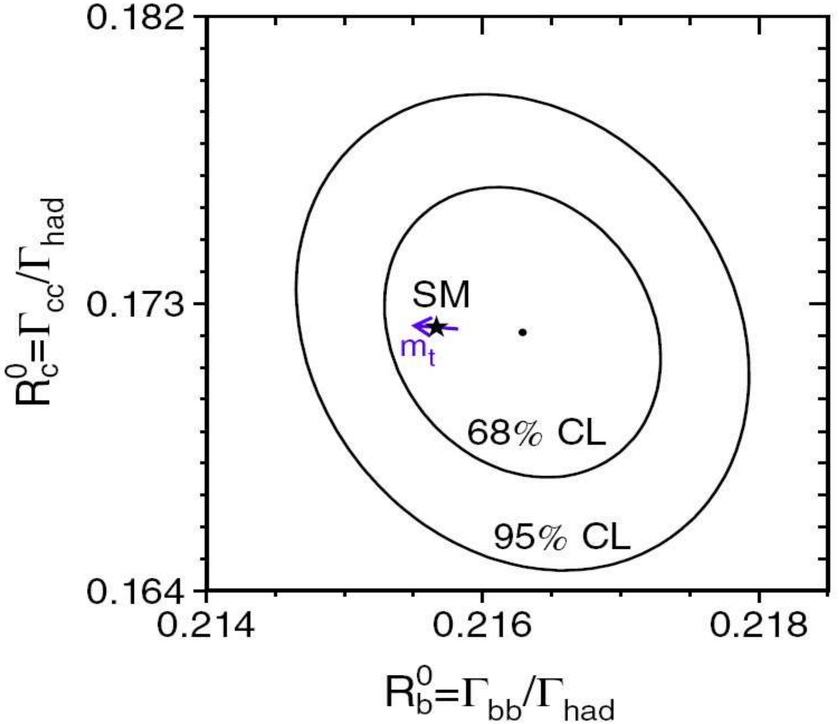
$\rho_l = 1.0050 \pm 0.0010$

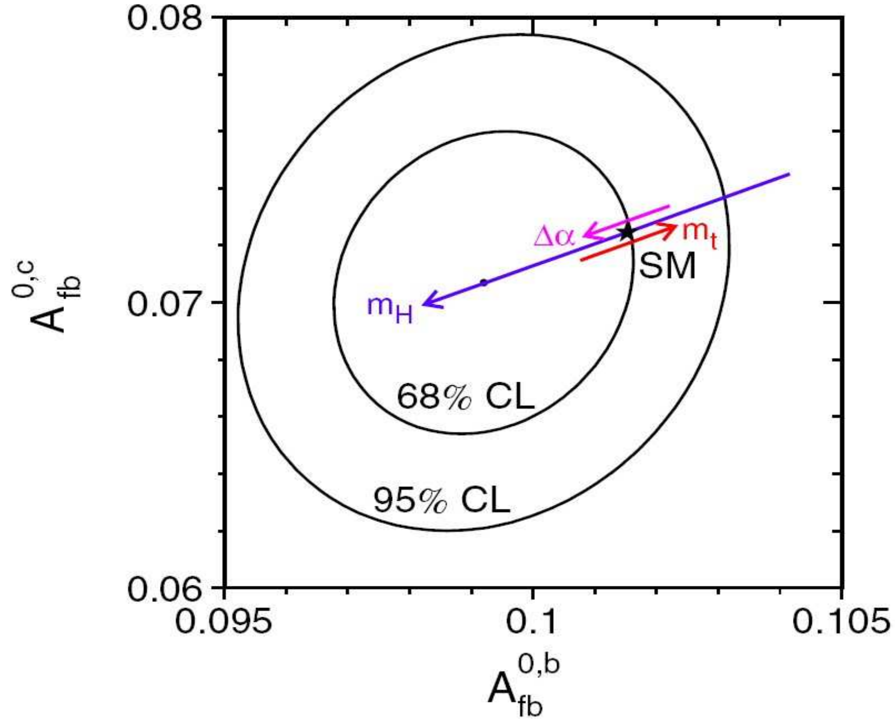
$\rightarrow$ EW radiative corrections beyond QED needed



$Z \rightarrow$ heavy quarks

Two important EW measurements: b partial width, R_b and A_{FB}^b

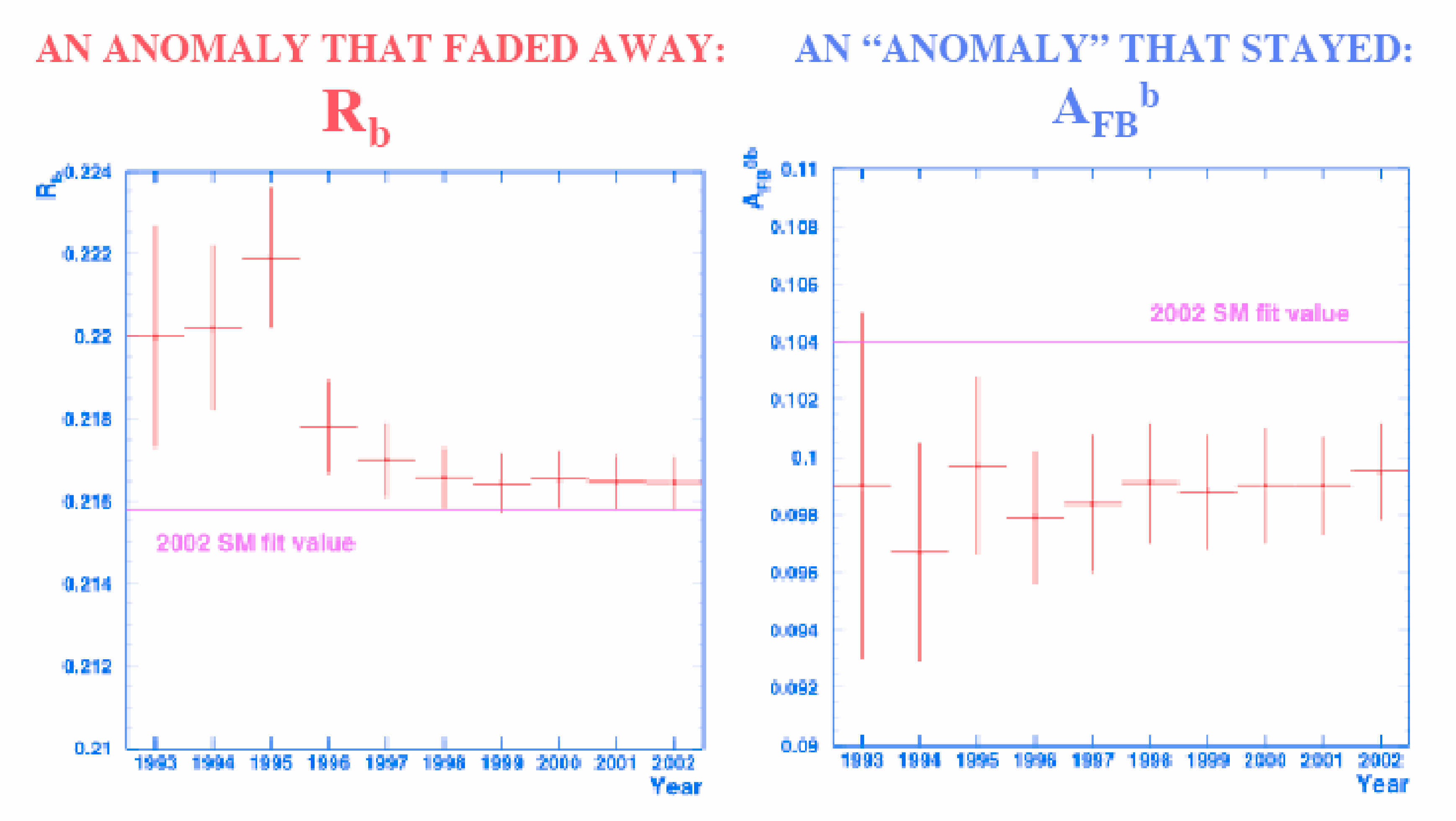




$R_b=0.21629 \pm 0.00066$
$\pm 0.00044_{stat}$

$A_{FB}^b = 0.0992 \pm 0.0016$
$\pm 0.0014_{stat}$

Z → b quarks

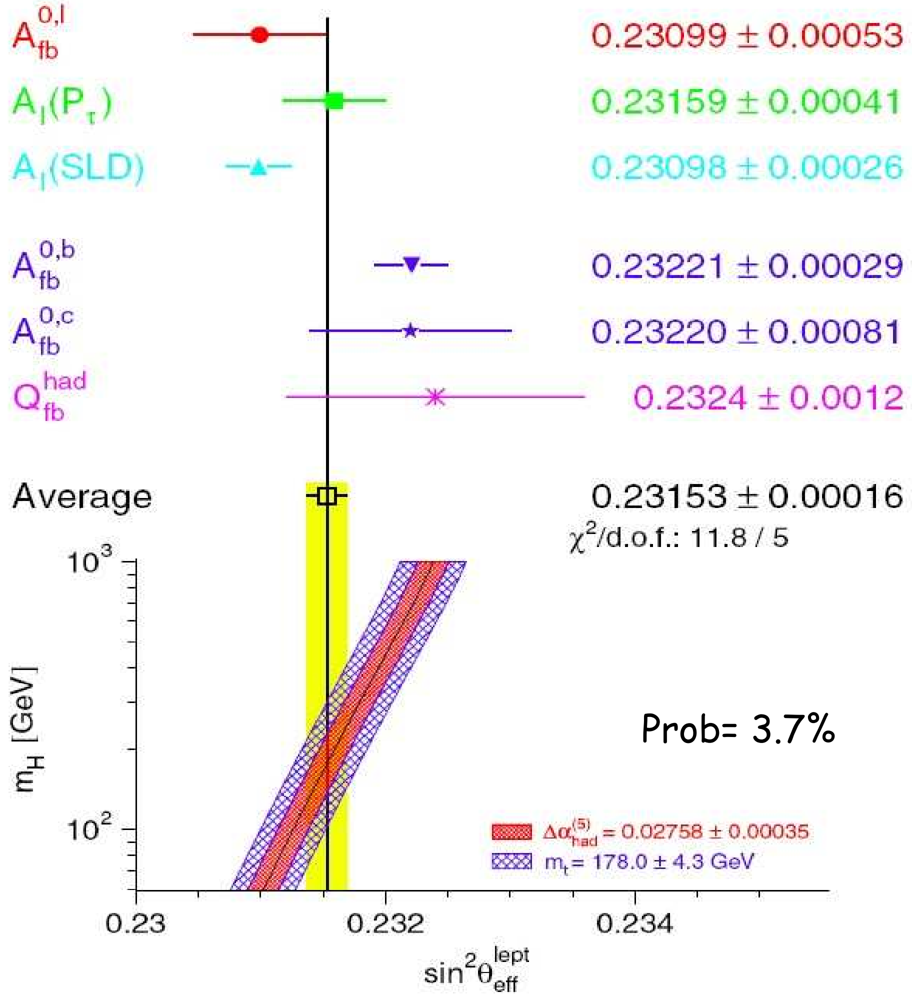


AN ANOMALY THAT FADED AWAY:
R_b
AN "ANOMALY" THAT STAYED:
$A_{FB}{}^{b}$
2002 SM fit value
2002 SM fit value
Year
Year

Z asymmetries ($\sin^2\theta_{eff}^{lept}$)

Effective weak leptonic mixing angle $\sin^2\theta_{eff}^{lept}$

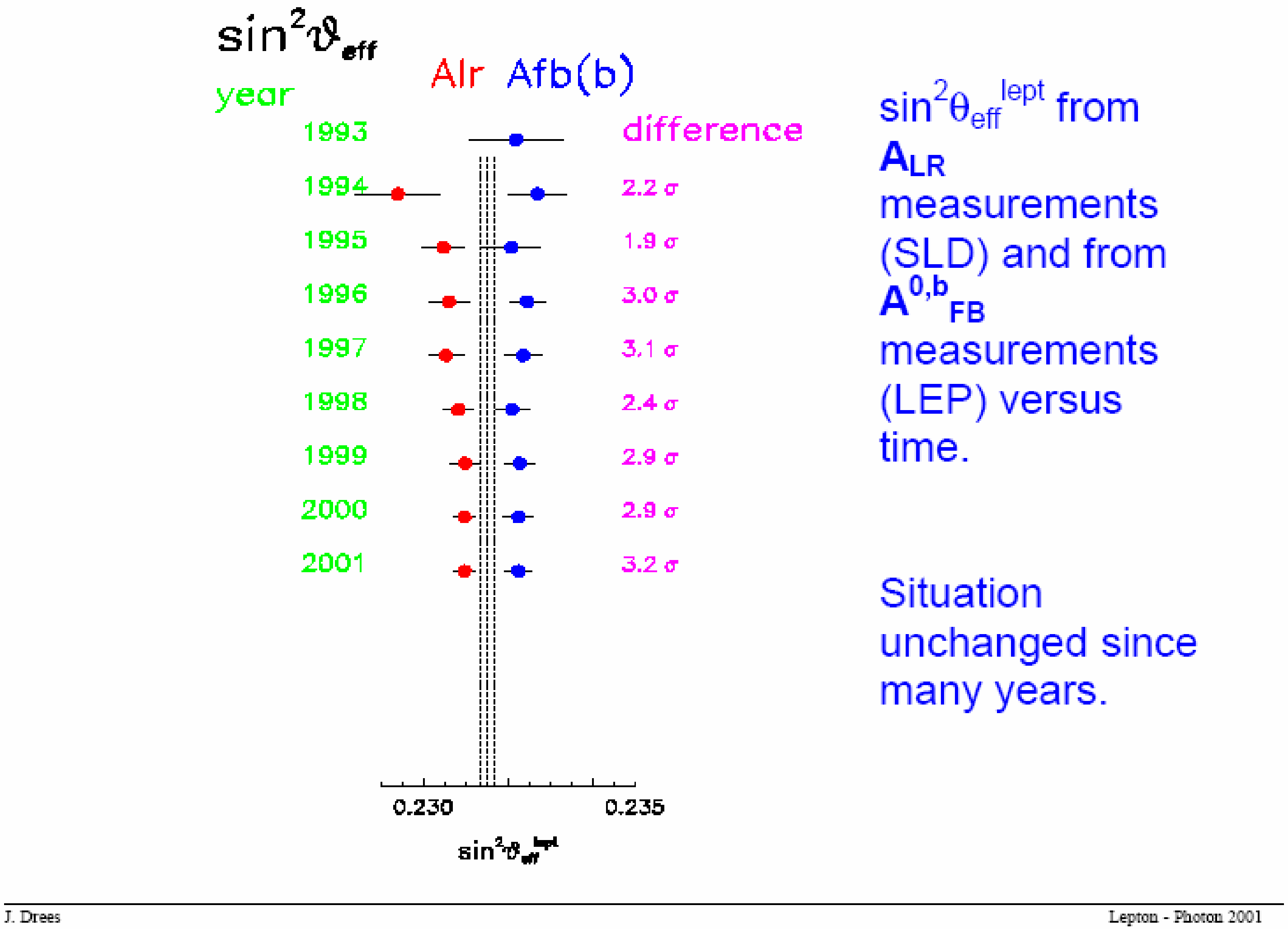
$$\sin^2\theta_{\rm eff} = \frac{1}{4\,|Q_f|}\left(1 - \mathrm{Re}\frac{g_V^f}{g_A^f}\right)$$



$\sin^2\theta_{eff}$ from A_l(SLD) and A^b_{FB} differ by 3.2 σ!

- non-Gaussian errors in A_{FB}?
- statistical fluctuation?
- ???

Z asymmetries ($\sin^2\theta_{eff}^{lept}$)



$\sin^2\theta_{eff}^{lept}$ from $\mathbf{A_{LR}}$ measurements (SLD) and from $\mathbf{A^{0,b}_{FB}}$ measurements (LEP) versus time.

Situation unchanged since many years.

A lepton with strong interactions, the Tau

The τ can decay hadronically, which makes it a unique tool for studying QCD in a clean way.

Using the fraction of τ decays into hadrons:

$$R_\tau = \frac{\Gamma(\tau \to X_h \nu_\tau)}{\Gamma(\tau^- \to e^- \overline{\nu}_e \nu_\tau)} = \frac{1}{B_e} - 1 - \frac{B_\mu}{B_e} = 3.641 \pm 0.011$$

This ratio was evaluated from theory (O.P.E.) as:

$$R_\tau = 3\left(|V_{ud}|^2 + |V_{us}|^2\right) S_{EW} \left[1 + \delta'_{EW} + \delta^P + \delta^{NP}\right]\ ;\ S_{EW} = 1.0194 \text{ and } \delta'_{EW} = 0.0010$$

Integral along the physical cut $\Leftrightarrow$ contour integral at $s \simeq m_\tau^2$

Dominant corrections to R_τ are from perturbative QCD

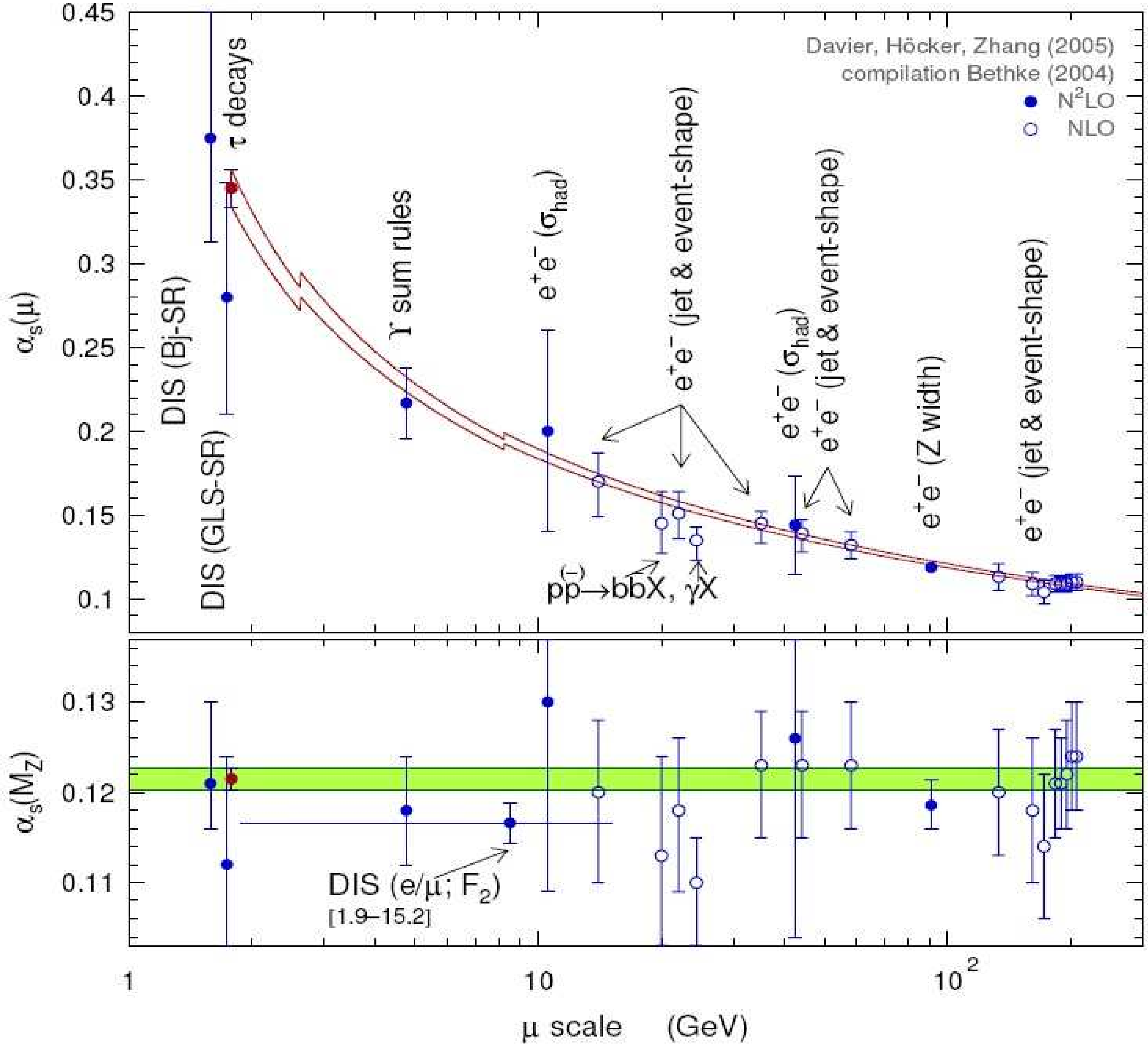
$$\delta^P = \frac{\alpha_s(m_\tau^2)}{\pi} + 5.2023\left(\frac{\alpha_s(m_\tau^2)}{\pi}\right)^2 + 26.366\left(\frac{\alpha_s(m_\tau^2)}{\pi}\right)^3 + (78.003 + K_4)\left(\frac{\alpha_s(m_\tau^2)}{\pi}\right)^4 + \mathcal{O}$$

Non-perturbative corrections behave as:

$$\delta^{NP} \simeq \mathcal{O}\left(\frac{m_q}{m_\tau}\right)^2 + \sum_{D=4,6,.} C_D(\mu)\frac{< O >_D}{m_\tau^D};\ C_D(\mu) \text{ are short distance coefficients}$$

Hadronic Tau decays, $\alpha_s(m_\tau)$

running of strong coupling constant



$\alpha_s(m_\tau) = 0.345$
$\pm 0.004_{exp}$
$\pm 0.009_{th}$

$\alpha_s(m_\tau)$ together with $\alpha_s(m_Z)$ from the global electroweak fit, is the most accurate test of asymptotic freedom:

α_s at m_Z:

from τ	0.1208 ±0.0025
from Γ_{had}	0.119 ±0.003

SM fits

SM: Each observable calculated as a function of:

$\Delta\alpha_{had}$, $\alpha_s(M_Z)$, M_Z, M_{top}, M_{Higgs}

Therefore, the input parameters are chosen to be:

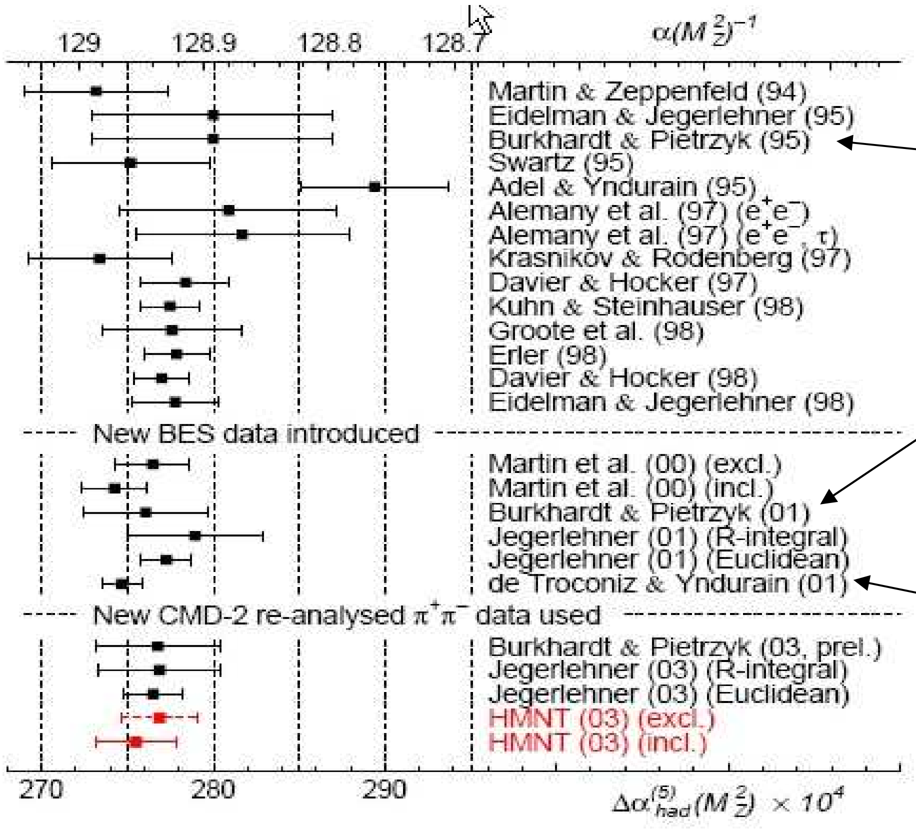
$\alpha^{-1}(0)$	$= 137.03599877(40)$	$\approx 3\times10^{-9}$
$\alpha_s(M_Z)$	$= 0.118(2)$	$\approx 2\times10^{-2}$
$G_\mu\ (m_\mu)$	$= 1.16637(1)\times 10^{-5}\ GeV^{-2}$	$\approx 9\times10^{-6}$
m_Z	$= 91.1875(21)\ GeV$	$\approx 2\times10^{-5}$

But… the relevant scale is $s \approx M^2_Z$ …

$$\alpha(s) = \alpha(0) / [1 - \Delta\alpha_{e\mu\tau}(s) - \Delta\alpha_{top}(s) - \Delta\alpha_{had}(s)\ ]$$

$s=M_Z^2$ 0.0315 small 0.0280 – 0.0275

$\Delta\alpha_{had}(M_Z)$



At end of LEP $\Delta\alpha_{had}$ became limiting uncertainty in SM fits.

$\Delta\alpha_{had}(M_Z)=0.02804\pm0.00065$

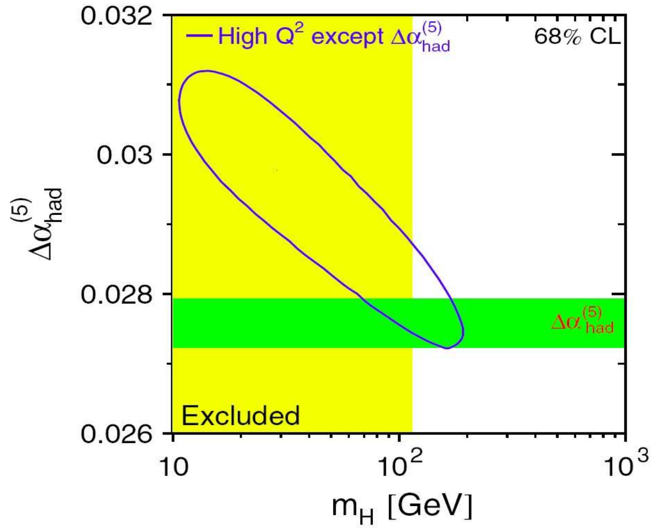
Post LEP measurements from BES and CMD-2 improvement.

$\Delta\alpha_{had}(M_Z)=0.02758\pm0.00035$

This value is used by EWWG

Using perturbative QCD

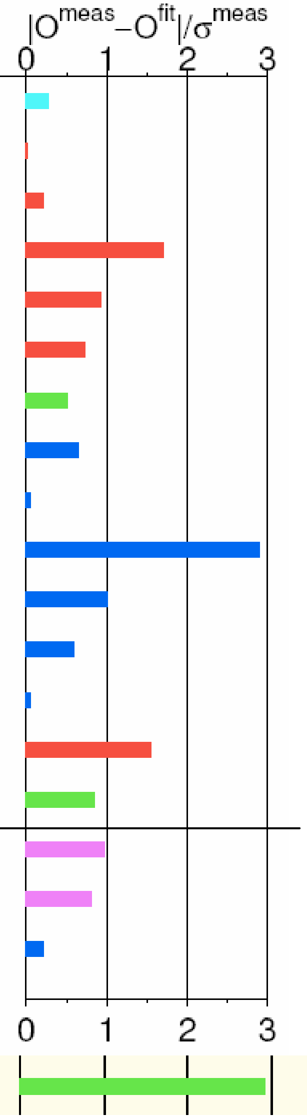
$\Delta\alpha_{had}(M_Z)=0.02749\pm0.00012$



LEP Standard Model Fit

2007

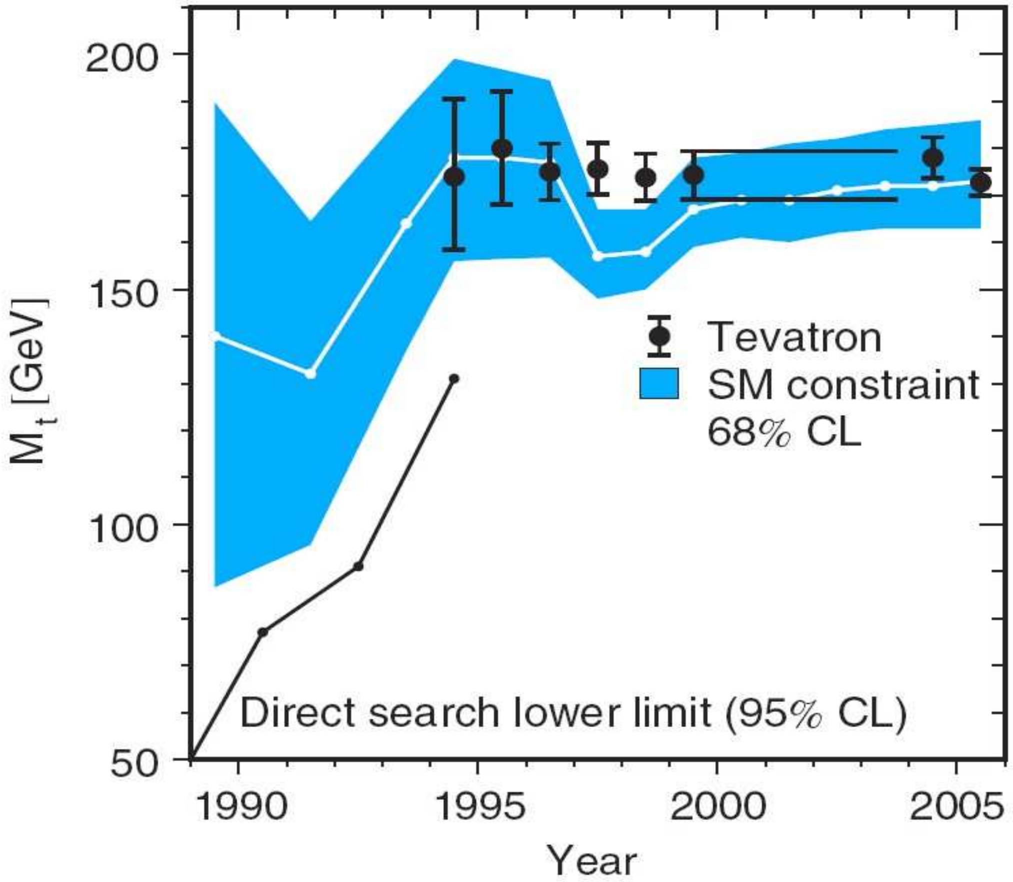
		Measurement	Fit
	$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
Z line shape	m_Z [GeV]	91.1875 ± 0.0021	91.1875
Z line shape	Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
Z line shape	σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
Z line shape	R_l	20.767 ± 0.025	20.744
Z line shape	$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
tau polarization	$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
heavy flavour	R_b	0.21629 ± 0.00066	0.21586
heavy flavour	R_c	0.1721 ± 0.0030	0.1722
heavy flavour	$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
heavy flavour	$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
heavy flavour	A_b	0.923 ± 0.020	0.935
heavy flavour	A_c	0.670 ± 0.027	0.668
	A_l(SLD)	0.1513 ± 0.0021	0.1481
	$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
	m_W [GeV]	80.398 ± 0.025	80.374
	Γ_W [GeV]	2.140 ± 0.060	2.091
	m_t [GeV]	170.9 ± 1.8	171.3
NuTeV	$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229

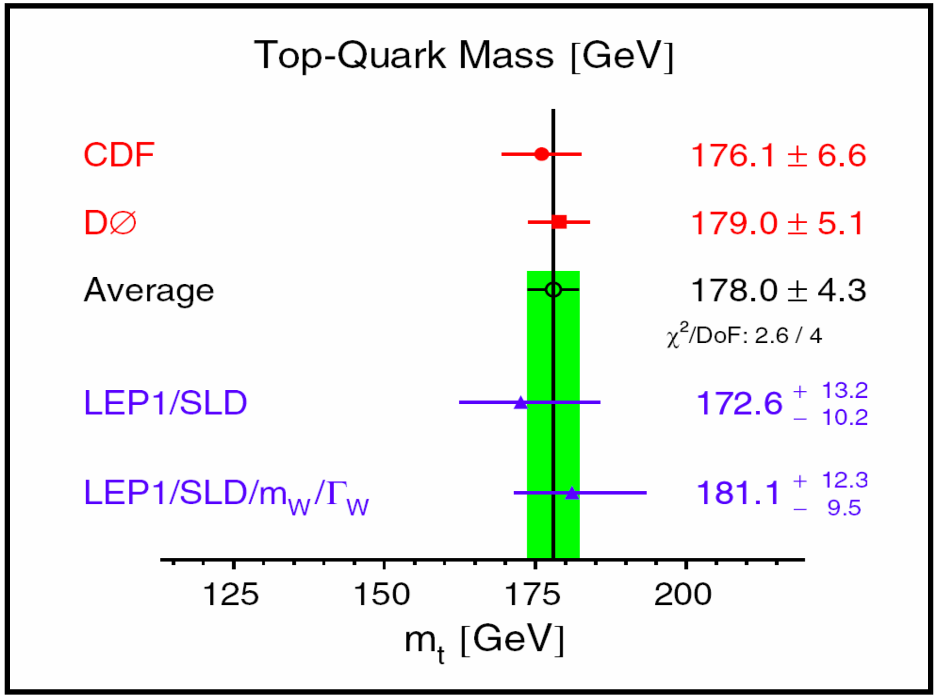


χ^2/dof = 18.2/13 (15%)

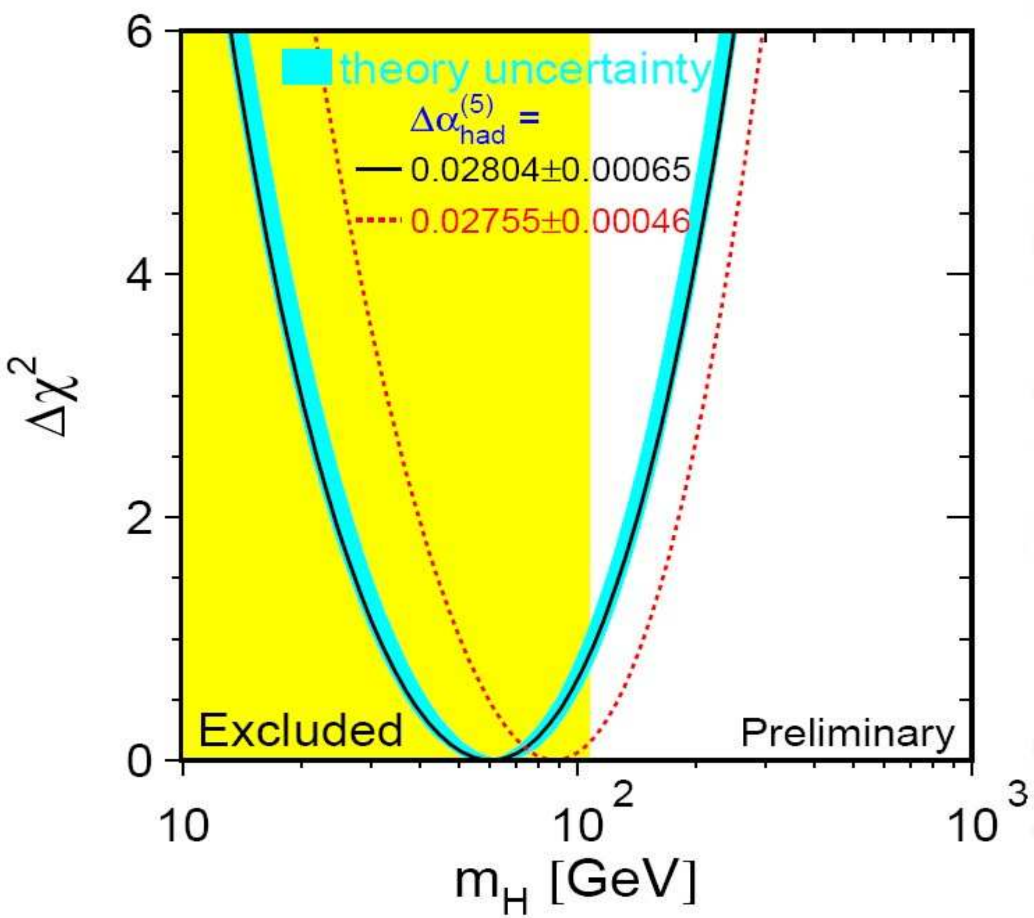
The TOP, indirect versus direct top-mass measurement

Through radiative correction in SM,
predict m_{top} from Z data



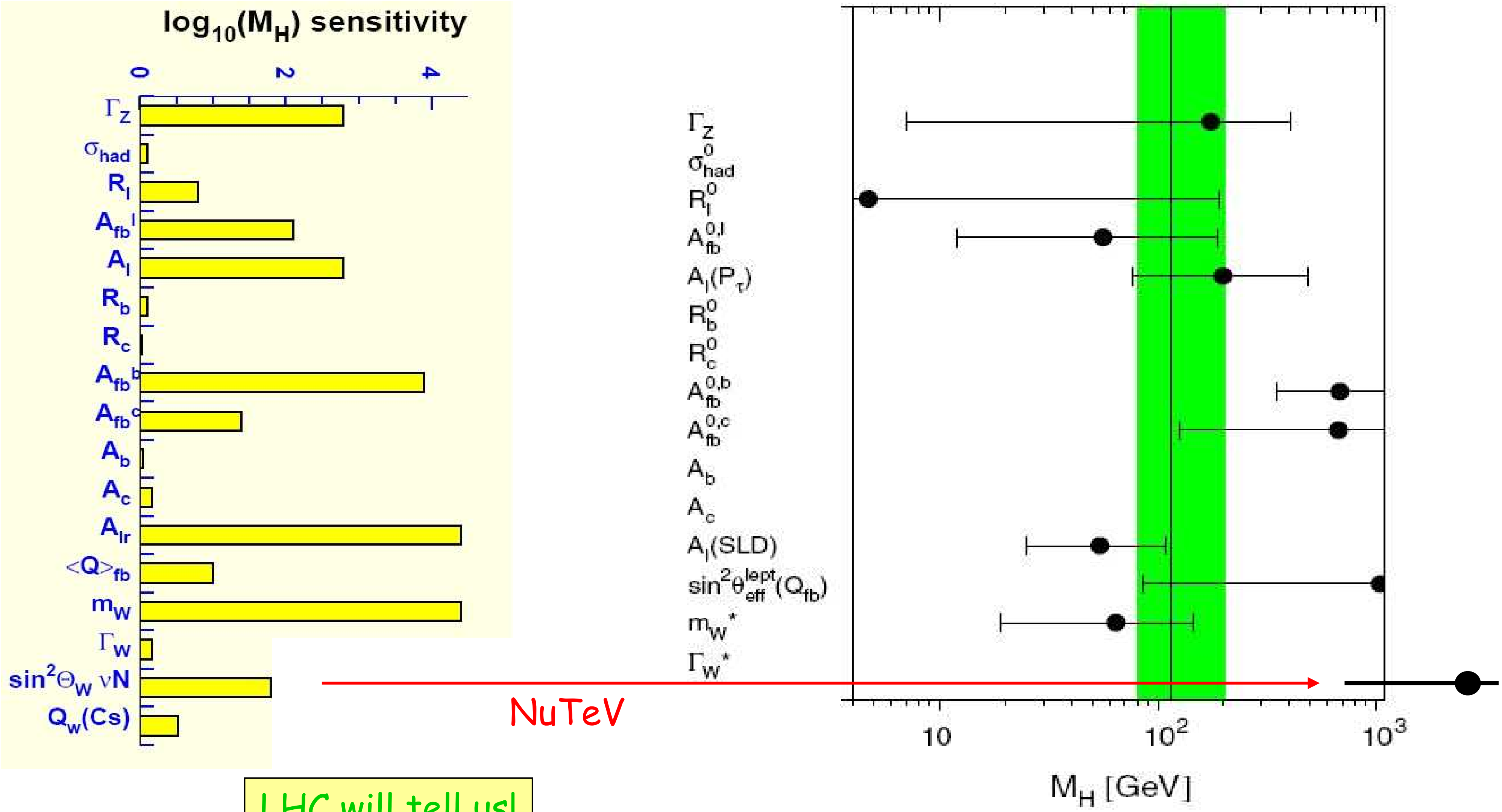


LEP Standard Model Fit



→ Higgs boson seems to be light, M_H < 150 GeV

Higgs Mass Sensitivity

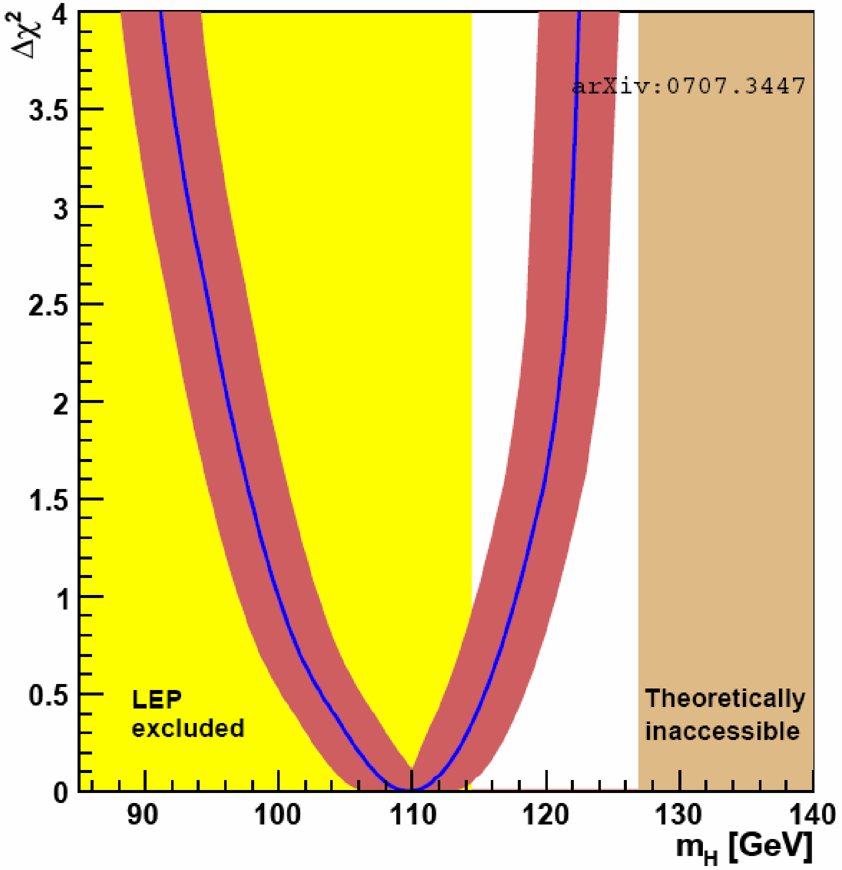


LHC will tell us!

CMSSM fits!

Red band plot:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]



$$M_h = 110^{+8}_{-10}\,(\text{exp}) \pm 3(\text{theo})\ \text{GeV}$$

The Contributions of Krakow Group

References in "*Precision Electroweak Measurements on the Z Resonance"* by the LEP and SLD Collabs.

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E.Barbiero, B.vanEijk, Z.Was, Comput.Phys.Commun.66(1991)115,CERN-TH7033/93(**PHOTOS**).

[252] G.Altarelli,R.Barbieri, S.Jadach,Nucl.Phys.B369(1992)3–32;

Conclusion

- Doing physics at LEP was an outstanding collaborative experience!
  - The precision results firmly established the SM, tested at the ‰ level.
    - LHC will soon allow us to see beyond the SM.